Root Cause Analysis

Large Hadron Collider

Magnet System Failure

Prepared For

Fermilab Research Alliance (FRA)

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Acknowledgements

The team wishes recognize the efforts of the individuals contributing to the US LHC project. It is clear to the Root Cause Analysis Team (RCAT) that issues that arose during the LHC project were not from a lack of dedication, expertise of the individuals involved in the design and fabrication, or desire to see the LHC a success. All individuals interviewed were extremely dismayed at the events that have occurred and were dedicated to making expeditious and technically-correct repairs.

Fermilab, CERN, LBNL, BNL and DOE professionals encountered by the team were open and frank during interviews and in written statements, and seemed genuinely interested in being part of the solution to reduce the likelihood of recurrence. The team greatly appreciates the support demonstrated and the Fermilab commitment to the subsequent success of this root cause analysis.

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Executive Summary

Event

Fermilab led an inter-laboratory project to provide critical components for the Large Hadron Collider (LHC) at the CERN Laboratory in Geneva, Switzerland. During the initial hardware commissioning phase there were two failures of the Fermilab supplied equipment.

A root cause analysis (RCA) was performed to determine the cause of the failures and to offer recommendations to reduce the risk of recurrence during future design and manufacturing initiatives.

Direct and Root Causes

The RCA Team (RCAT) determined common direct and root causes are applicable to both failures:

Direct Cause – In both instances the Fermilab design process did not account for the environment in which the assembled components would operate. In the first event an improperly designed heat exchanger pipe failed during a test at less than the 20 bar static normal operating limit. In the second event the application of design maximum pressure of 25 bar (asymmetric) pressure caused longitudinal movement of quadrupole magnets and subsequent breakage of internal support structures and cryogenic connections. The failure occurred at less than 20 bar because the dynamic application of pressure was not considered in the design of the support structure.

Root Cause – Fermilab engineering management controls do not include codified, standard design process requirements that include an integrated systems design, design review, and documentation recording and archival process. Instead, Fermilab relies upon individual contributors to obtain review of design basis calculations and recognition of interface and integration requirements. In both instances, the lack of documentation and in-depth review resulted in critical design errors being missed until the components were tested *in situ* at CERN.

Contributing Causes

There are a number of contributing causes that can be described as failed or non-existent barriers. These barriers, if they had been established or used effectively, should have caught the design errors prior to the systems tests at CERN. These are addressed as contributing causes in the body of the report.

Root Cause Impact

Putting this project in perspective, the published overrun of the project, including the repairs to the Fermilab components, is less than 10% of the total project cost. Although costly in terms of dollars spent, this overrun is not extraordinary and is within industry averages for projects of this size and complexity. Even so, Fermilab commissioned a root cause analysis. Clearly, the concern is not simply project cost or schedule; rather it is the perception of Fermilab's technical engineering capabilities and its ability to manage large, complex projects. The inference being that if Fermilab cannot manage the technical quality of one portion of the LHC program without discovering and eradicating design errors prior to fabrication, how can it be entrusted to manage other large projects such as Project 'X' and the International Linear Collider?

The Case for Change

Fermilab is unique in the high energy physics (HEP) community in that it has, for years, been the operator of the most powerful particle accelerator in the world. It now finds itself on the cusp of a time when that honor is going to pass to another facility on another continent. As such, several key decisions are being made regarding Fermilab: whether to shut down or modify the Tevatron for other use, whether to fund new experiments, and the level of involvement in international collaborations such as Project 'X' and the ILC.

Further complicating matters, Fermilab's most senior, knowledgeable personnel are of, or are approaching, retirement age. Unfortunately, a knowledge database or engineering lessons learned program has never been created to pass on the information and basis for decisions and design to incoming physicists and engineers. This detracts from one of the key discriminators that Fermilab has today – being one of the most experienced designers and fabricators of large machines in the high energy physics community.

In order to remain a viable laboratory Fermilab must have the reputation of delivering positive scientific results while exhibiting good business, engineering, and project management practices.

These concerns dictate the need for a cultural shift. In order to maximize the availability of funds to support R&D and other new programs, and to make the most use of available funds, Fermilab must improve its processes. This does not mean limiting the freedom of scientific personnel to do research and development; it does mean that there needs to be a shift in perspective: capture and archive decisions and results of testing for future users, engineers, and scientists; changing the conduct of engineering reviews to focus on design basis and component integration; improving project management practices such as being more aware of risk and how to mitigate it; and managing for successful outcomes the first time thereby limiting the amount of re-work and expense.

In summary, it is incumbent on Fermilab to ensure its engineering and management processes and controls are among the best in the HEP community; well established and well-executed. By demonstrating such technical and management excellence, Fermilab can improve its chances of remaining a viable laboratory well into the future.

Recommendations

Recommendations are discussed in the body of the report and include suggestions for improvement in five areas:

- Project planning and execution
- Design and engineering processes
- Training
- Quality Assurance
- Need to establish inter-laboratory and international project collaboration processes

Generally, the recommendations can be implemented with minimal overall cost and/or in lieu of current requirements or processes thereby limiting the addition of new layers of administration. For brevity, a compiled list of recommended actions without discussion is presented on the next page.

Conclusion

The Team appreciates the contribution of the LHC project participants during the conduct of the RCA. The participants were open and responsive to questions and provided constructive feedback when recommendations were discussed. The Team believes that the recommendations, if adopted, will complement the impressive skills, experience and motivation of the Fermilab professionals and position them for future projects and laboratory viability.

Recommended Actions

- Project planning and execution
    - Enhance the project kickoff process to include:
        - Approach
        - Risk identification and mitigation
        - Project constraints (budget, schedule, manpower, and operational issues)
        - Key project members roles and responsibilities
        - Identification of inter-divisional participation
        - Test plans and testing environment
        - Identification of known operational environment and constraints
        - Clear identification of specifications or design requirements
    - Enhance Project Controls to include:
        - EVMS used for project management
        - Development of more comprehensive Basis of Estimates for all portions of the project and ensure that engineering and fabrication quality assurance is included adequately in the estimates.
            - Develop and maintain a resource-loaded baseline schedule
        - Risk-based change management process
        - Refined contingency development and management processes to include use of management reserves
        - Require that all project schedules include specific activities, milestones and adequate time allowances for:
            - Engineering review, testing and other QA activities
            - Formal break point milestone to transition from R&D to production
            - Testing and test program development
        - Establish formal project documentation usage requirements
            - Re-visit risk analysis at prescribed intervals to ensure project issues are known and resolved
    - Establish risk management position for participation in all projects of significant size or complexity
- Design and Engineering Process
    - Establish a Fermilab Chief Engineer position reporting to the Director
    - Require that all project organizations include a specific role for systems integration manager
        - Define integration requirements in engineering control documentation
    - Create and manage a laboratory wide Fermilab design/engineering manual and implementing procedures including configuration control systems and processes
        - Design reviews
            - Establish templates and checklists that must be included in design reviews
            - Perform reviews aimed at determining technical specifications are met
        - Establish requirements to provide independent technical reviews

        - Establish design review formats and designate the appropriate time to allow checks of design calculations
        - Define archival requirements for design basis calculations and R&D results
        - Define required internal design basis calculation cross-checks and review
    - Develop a risk-based change management process for use during design efforts
    - Differentiate critical design elements and how to control them
- Training
    - Establish or procure formal training for Project managers
    - Develop orientation for personnel involved with design efforts to familiarize them with Fermilab processes and procedures.
- Quality Assurance
    - Establish a risk-based QA program at Fermilab (underway)
    - Establish a lessons learned program and database to capture and share lessons from previous projects among all collaborating labs
    - Establish key QA milestones in project budgets and schedules
    - Establish a QA inspection program that includes minimum standards for inspection of manufactured articles and identification of quality assurance inspectors
- Commission a Process Improvement Team to recommend project execution guidelines and requirements for Fermilab project managers to follow for both inter-laboratory and international collaborative projects.

Description of Events

Fermilab led a consortium of three U.S. laboratories (Fermilab, Brookhaven National Laboratory, and Lawrence Berkeley National Laboratory) that have supplied critical components to the Large Hadron Collider, currently entering its commissioning phase at the CERN Laboratory in Geneva, Switzerland. These components were designed, fabricated, and delivered to CERN over the period 1998-2006. During the initial hardware commissioning phase there were two failures of Fermilab supplied equipment:

1) On November 25, 2006 a heat exchanger internal to one of the Fermilab supplied magnets collapsed in a pressure test
2) On March 27, 2007 structural supports internal to one of the Fermilab supplied magnets failed in a pressure test.

Purpose and Scope

The Fermilab Director commissioned a root cause analysis (RCA) to determine the cause(s) of the failure and to offer recommendations to prevent similar issues from recurring during future design and manufacturing initiatives. More specifically the RCA team was charged to undertake an investigation and analysis in the following areas:

- Conduct a root cause analysis that identifies how deficiencies in the quadrupole support structures, and the heat exchanger, went unrecognized until the components were under final test at CERN.
- Recommend changes to Fermilab's procedures and processes to prevent recurrence.

Approach

The RCA team consisted of independent experts from Fermilab, Spallation Neutron Source (SNS), and EG&G/URS to perform the RCA as shown in Attachment 1. None of the team members had been directly involved in the LHC magnet project. The team reviewed project documentation, Fermilab procedures manuals, and conducted interviews of Fermilab, Berkeley, Brookhaven, and CERN project personnel and Fermilab support staff, in eight specific areas:

- Project Management
- Agreements
- Specifications
- Design
- Procurement & Construction
- Acceptance & Testing
- Delivery
- Commissioning & Startup

A list of personnel interviewed as part of this root cause analysis is contained in Attachment 2.

The team, as charged, reviewed design, fabrication, assembly, QA and testing processes used to produce the Fermilab LHC Interaction Region Magnets and integrated DFBXs to determine the causes of failures and to make recommendations to reduce the likelihood of recurrence.

Causes were identified using a variety of root cause tools including TapRoot®[1], five-why's and Ishikawa[2] diagramming. As part of the root cause, the team performed a review to answer three basic questions about Fermilab project execution practices:

1) Did Fermilab follow its own processes?
2) Do Fermilab processes follow best practices?
3) What changes are recommended to align Fermilab processes with generally accepted standards and best practices?

Finally, the team made every attempt to make sure that recommendations are targeted and actionable. The recommendations are intended to revise or enhance current requirements; thereby reducing the cost of implementation to make them more practicable for Fermilab.

Report Arrangement

The report presents the causes for the Heat Exchanger and Quadrupole failures. The direct and contributing causes are related, but are presented separately for clarity.

For purposes of this report, it is understood that the quadrupole magnet did not fail; rather the cold mass support structure elements were damaged when the cold mass moved under pressurization test. For ease of understanding, the report uses nomenclature commonly used at Fermilab; calling it the quadrupole failure.

[1] TapRoot® is an Incident Investigation System which provides teams with a procedure and techniques to perform an in-depth review of an incident or event. The system looks for both human performance and equipment causes of incidents or events and is flexible to allow review team leaders to select only the techniques that are applicable to the event being reviewed.

[2] An Ishikawa diagram, commonly referred to as a fishbone diagram, is a visualization and knowledge organization tool. It allows the users to collect the ideas of a group in a systematic way that facilitates the understanding and ultimate diagnosis of a problem. The diagnosis leads the group in a systematic way to discover the root, direct, and contributing causes of a problem.

The document contains sections for each, arranged as follows:

Quadrupole Cause Summary – Presents summary level causes (direct, contributing, and root) in outline form, as identified using the TapRoot® process.
Quadrupole Cause Summary Discussion – Following the Cause Summary outline, the discussions are arranged into categories of Direct and Contributing Causes.
Heat Exchanger Cause Summary – Presents summary level causes (direct, contributing, and root) in outline form, as identified using the TapRoot® process.
Heat Exchanger Cause Summary Discussion – Following the Cause Summary outline, the discussions are arranged into categories of Direct and Contributing Causes.
Common Cause Summary – Contributing Causes germane to both incidents
Root Cause Discussion – Presentation of root cause of the failures.
Recommendations – Solutions to problems discussed
Supporting Documentation – Explanation of documentation used as a source of information when assessing performance and to identify Direct, Contributing, and Root Causes.

Root Cause Process

In discussions with Fermilab management prior to starting this analysis, it was agreed that the team would (1) use the TapRoot® system, a very structured process to identify causes of an event or issue and (2) focus on the adequacy of Fermilab's processes. TapRoot® was chosen because it uses fault tree analysis to determine the cause of an issue that drives participants beyond the human performance to the cause behind the performance, expressed in terms of system or process issues.

The TapRoot® system guides reviewers performing root cause analysis through fault trees in both equipment design and human performance factors. The TapRoot® analysis related to human factors considers individual, team, and management performance. The team used these factors to develop common causal factors related to system and process issues as depicted in the quadrupole and heat exchanger outlines.

Direct and Contributing Causes are presented separately for the Quadrupole and Heat Exchanger failures.

Quadrupole Cause Summary

The TapRoot® standard terms are presented in the outline below. To be consistent with the TapRoot process, the team is using these standard terms, though in the discussion following the outline we have used the TapRoot standard terms in context of Fermilab processes

1) Equipment Difficulty
    a. Design
        i. Design Specifications
            1. Problem Not Anticipated
                a. Equipment Environment Not Considered
            2. Specifications Less Than Adequate
        ii. Design Review
            1. Independent Review Less Than Adequate
2) Human Performance Difficulty
    a. Procedures
        i. Not Used / Not Followed
            1. No Procedure
            2. Procedure Use Not Required But Should Be
    b. Training
        i. No Training
            1. Task Not Analyzed
    c. Quality Control
        i. Quality Control Less Than Adequate
            1. Inspection Instructions Less Than Adequate
            2. Inspection Techniques Less Than Adequate
    d. Communications
        i. No Communication or Not Timely
            1. No Method Available – Not Required
    e. Management System
        i. Standards, Policies, or Administrative Controls
            1. Incomplete
        ii. Oversight / Employee Relations
            1. Audits And Evaluations (A & E) Lack Depth
            2. A & E Not Independent

Quadrupole Cause Summary Discussion

This section discusses the causal factors used in the TapRoot® system in context of Fermilab systems and processes. Each of the headers used in this section tie directly to the causal factor outline.

Direct Cause

1)a.i.1.a - Equipment Environment Not Considered

The Fermilab LHC Interaction Region (IR) magnets were designed as a collection of components that were assembled as a "quadrupole magnet" system. The design effort did not consider the components together as an assembled system (i.e. triplet with an integral DFBX) and did not analyze the assembled component system in its intended, operational environment. The result was the pressure vessels and support structures were built to withstand the static pressure requirements, but did not consider the application of the pressure under dynamic load. Under test in the LHC tunnel, the quadrupole magnets moved longitudinally damaging internal support structures.

Contributing Causes

1)a.i.2 - Specifications Less Than Adequate

Early in the project, CERN provided boundary conditions and known specifications; however, other required specifications were not defined until much later in the design and construction phases. As would be expected during a research and development effort, detailed specification development is part of the ongoing process; however, issues evolved that caused concern with the engineers fulfilling the design and fabrication role:

1. Identification of interface and operational/performance specifications did not characteristically precede the development and fabrication of equipment.
    a. Although specifications were developed early in the production cycle as drafts, they evolved during the production phase and were not finalized until late in the project cycle.
    b. Engineering staff focused on the specifications for major components such as magnets in a linear fashion, and not adequately in advance of the production effort to allow independent reviews and approvals.

1)a.ii.1 - Independent Review Less Than Adequate

The independent review process used at Fermilab varied by component and technical specialty, was not well documented, and was not comprehensive.

Engineers are not required to have their design basis calculations reviewed during the R&D process. Any internal design review that did occur was based upon the judgment of the individual engineers and scientists, and not specified by Fermilab design process procedures, the project QA plan, or team leaders. The reviews were not comprehensive with respect systems analysis, inter-disciplinary participation and engagement of technical specialists who were not affiliated with the respective national labs and universities participating in the LHC Program.

The programmed independent reviews (conceptual design review, two engineering design reviews, and production readiness review) were scheduled around critical components and not system assemblies. The reviews were typically PowerPoint® presentations that focused on issues or challenges that the design component leader selected. The reviews did not validate assumptions, evidence that specifications were being adequately met, or verify design basis calculations and/or conduct a detailed review of drawings. Although issues were captured and corrective actions taken, the reviews were not performed at a level of detail sufficient to allow the capture of the errors in the Fermilab supplied components. While a PowerPoint® type of review is adequate for conceptual design, it does not, by virtue of its presentation format, accommodate a comprehensive review of complex components and systems as required during engineering design or readiness reviews.

Design reviews and design review presentations were performed by personnel recognized as experts within the high energy physics community. When presenters are recognized experts, the reviewers' level of in-depth questioning was less probing in deference to the individual's stature. Furthermore, while some of these experts may have been independent from the perspective of not having worked personally on the LHC project, they knew the project participants well. In many cases they would have their projects reviewed by the same Fermilab personnel being reviewed. This created a "reciprocal" situation of mutual benefit and removed an element of independence, as in a professional courtesy afforded personnel that work in the same industry.

Personnel interviewed pointed out that they had initiated an in-depth design review of the Berkeley DFBX design when errors were discovered but failed to conclude that such a review would be appropriate for the design work being accomplished at Fermilab.

The review process is characterized by the following three issues:

1. There is no requirement that drives internal review of design basis calculations.
2. There is no comprehensive process to drive an integrated, system-focused, internal project review during design/development.
3. The external design reviews are neither detailed nor independent.

<u>2)a.i.1 - No Procedure</u>

The engineering design process is not codified or standardized at Fermilab resulting in a wide variety of approaches being used by designers of the various components.

Sub-elements of the design process are codified in the Fermilab Environmental, Safety, and Health Manual (FESHM). The FESHM requires the capture of summary-level information for designs that affect life-safety code, such as pressure vessels, in engineering design notes. Nevertheless components that require FESHM compliance do not require archival of standardized, organized and documented design assumptions, design calculations, or ideas and concepts tried and abandoned.

Documentation of design efforts vary by individual. Some keep exhaustive notes and ledgers containing basis of design while others do not. Further there is no central project record with design development documentation for future use or reference.

This decentralized component- and discipline-based design approach affected the systems integration with Q1s and Q3s coupled with Q2s. Interviews disclosed that the stress calculations for the Q2s were assumed to be representative and therefore applicable for Q1s and Q3s. This was incorrect because the pressure loads/stress was symmetrical for the Q2s and asymmetrical for the Q1s and Q3s when coupled with Q2s. Because the design approach focused on components and component systems there was no opportunity to validate or invalidate this design assumption based on a Systems Integration assessment.

Final design drawings are controlled and archived, but the engineering basis is not captured for use by others or outside the responsible organizational division.

<u>2)a.i.2 - Procedure Use Not Required But Should Be</u>

Technical Division (TD) has a Quality Assurance manual and more specifically the US LHC had a Quality Assurance manual, TD-2010, Version 2, that contains requirements for design phase tasks including documentation, reviews and archival of design basis information, and interface requirements. For the LHC, the Quality Assurance manual procedures were followed for the fabrication and assembly phase (as the manual is largely a codification of the “Traveler“ process). The procedures presented in the manual were only partially (or not at all) applied during the research and development or design phase activities. The interviewees that knew of the document’s existence confirmed this process, stating that the QA Manual is widely accepted as pertaining only to fabrication.

As the manual provides latitude for the PM to apply the requirements of the document to the project in the preamble, no violation of Fermilab procedure or policy occurred; however, conformity with the QA manual during the design phase, especially in the areas of cross-checking design basis calculations and integration, may have prevented the occurrence of the quadrupole failure.

Aside from the use and conformity with the processes described in the TD QA manual, the manual in and of itself was not structured for effective QA. As told to the team, the manual was developed to both codify TD QA practices and to cross reference Fermilab QA practices with CERN QA requirements. The QA manual was not developed to define QA processes customized and relevant to the multi-lab, multi-component and multi-national aspects of the US LHC project.

2)b.i.1 - Task Not Analyzed

"Task Not Analyzed" is a title from the TapRoot® fault tree and references determination of the training requirements for certain jobs and their associated tasks. None of the Fermilab tasks discussed in this section were analyzed for training requirements. Fermilab's on-site training programs are largely focused on Safety, Orientation, and Supervisor Training, such as General Employee Training and General Employee Radiological Training, Confined Space Entry, supervisory administrative and safety functions. These are used to ensure personnel are safe to move about the site and to allow entry into areas of risk. The training programs and new employee orientation do not guide technical staff in procedures and processes to document design efforts consistently or to understand the applicability and use of standards such as FESHM. In addition, Fermilab does not provide project managers with training on tools and techniques for guiding projects from idea and concept to successful completion such as integrated research and development efforts, team based reviews, and project controls (scheduling, organization, cost and budget management and information systems management).

Project Management – Project management is not a professional progression employment path at Fermilab, nor is it a position that personnel seek to occupy. Instead, the personnel that have championed a new concept or new experiment being considered are typically asked to serve as the project manager.

In general, personnel performing project management functions do so as a collateral duty while maintaining their primary focus on their areas of technical expertise. The newly established Fermilab Office of Project Management Oversight provides directional guidance to project managers in the earliest phases of a new experiment, or project, but does not provide the resources or functional involvement to guide the day-to-day operations. Testimony from interviewees indicated that the OPMO reviews are used to pressure project participants to conform to the Critical Decision point documentation and informational requirements of Fermilab and DOE, i.e. DOE O 413.3, Program and Project Management for the Acquisition of Capital Assets, commonly referred to as "Lehman Reviews."

This approach results in managers performing project management functions to maintain compliance with reporting requirements at prescribed intervals rather than using project management tools to more effectively execute the project. As described in other areas of this report, project management plans should include tools, such as specific guidance for project integration and risk management, to help the PM manage the project. Without proper training in methods such as these, the PM is not fully equipped.

Engineering Function – The training and orientation process for technical professionals focuses on administrative HR and Safety issues. The process does not familiarize technical staff with procedures and standards to be followed for design, documentation reviews or QA. Furthermore the procedures and approaches used within TD and within other Divisions at Fermilab differ. This results in technical design procedures that are inconsistent within the Lab and varying levels of granularity in design basis documentation.

Quality Assurance Inspectors (QAI) – There is no formal training and no formal procedures to standardize the approach to inspect procured and manufactured items.

Without a standardized approach, there is no consistency in how items are inspected and tested. With standardization comes process and process training; ensuring those that are designated to perform this function do so to consistent levels established by Fermilab.

By setting a qualification standard, personnel will have demonstrated their proficiency before being relied upon to independently perform inspections of material received from vendors and to review and observe testing performed by fabricators such as dye-penetrant testing, ultrasonic testing, small-gauge measurements, etc.

2)c.i.1 - Inspection Instructions Less Than Adequate

The Traveler document used by Technical Division is an excellent practice that should be emulated/benchmarked by other laboratories. Even though it is a best practice, its use of the traveler needs improvement. The reviews performed by Fermilab design engineers are adequate; however, inspections by qualified QA personnel should precede the engineer's signatures to provide documented evidence that the article is built as required.

2)c.i.2 - Inspection Techniques Less Than Adequate

The Technical Division's use of traveler documents has matured and provides many positive results for Fermilab as a reference document for accelerator maintenance and operational enhancements. The travelers use stop and hold points for sign off by the originating design engineer to ensure the manufactured item is properly configured before allowing additional work to continue. The traveler document should however, contain steps or refer to an approved QA procedure for verification of fabrication elements. The personnel performing the task should be qualified in accordance with an approved Fermilab training program, developed by a Quality Assurance Inspector Level III. This will ensure consistent inspections by personnel trained to a minimum standard level, as demonstrated by a documented On-The-Job training program. These inspections are what the designer should be signing as complete. This will standardize the review process and free designers to perform other tasks.

Technical Division has an inspection group as part of the material control section; however, none are formally trained, qualified, or periodically re-qualified in accordance with a standard or quality assurance inspection program. Consequently, inspection efforts focus on dimensional and documentation checks or procedures in place or as requested by others: hence inspections are not per a QA program nor tailored to the project characteristics and requirements.

2)d.i.1 - No Method Available – Not Required

Quadrupole research and design development focused on components and a sequence of working from the inside out. Design disciplines in the cryogenics, mechanical, electrical, and physics areas focused on discrete elements. There were no formal design team meetings where development and progress issues were discussed in the presence of all team members and project leaders. Absent these internal group discussions there were no formal or informal processes to establish integration between the disparate groups during the development of individual components that collectively addressed systems integration issues.

During an R&D effort changes are expected and group discussion is required to analyze the changes and recognize the effect that one change has on the upstream and downstream components. Additionally, such discussions permit the identification of the impact of changes on previously designed components. Personnel interviewed indicated there were multiple meetings to discuss single component design issues, but none of a group manner that looked at the collection of components to discuss operational and performance design issues.

2)e.ii.1 - Audits And Evaluations (A & E) Lack Depth

Audits and evaluations by project management are designed to make certain that the project meets minimum requirements of DOE reviews, neither of which are performed at a level sufficient to discover the issues related to the LHC Quadruples.

In the case of the LHC project, Fermilab solicited a review by an expert at Argonne National Laboratory to perform what is now referred to as a Director's Review. This review addressed issues related to ensuring that the project was ready for the DOE review, which tends to focus on program management vice technical issues.

This review resulted in a comment that there was not enough contingency built into the project and that the project, the way it was constructed, would not be able to provide the equipment required for the budget allocated. Immediately following this Fermilab review, the DOE review concluded the opposite and informed Fermilab that it needed to decrease the contingency and add scope as it was "over-funded."

Circumstances related to the international nature of the LHC and the DOE agreement with CERN may have forced the decision on the Fermilab team. However, no information was presented to demonstrate that the DOE conclusions were refuted at the time and the resultant action was to accept the DOE's comment and add scope to the project. This action contributed to a project overrun reported at $1.5M of the $44M Fermilab portion of the project. Based upon review and interviews, it was determined that actual costs were much higher as it was Fermilab's practice to augment projects with personnel charging to general operating funds. An accounting review revealed that no mechanism exists to differentiate these costs; and therefore, no way to validate actual project costs.

LHC Project progress was measured using Earned Values among other measures. However, design efforts were not budgeted by task and determining percent complete was often based on time spent or non-measurable estimates. For example, design personnel reported time spent without regard to actual work completed and management portioned the cost over schedule items based upon personal estimation of work performed. This resulted in the perception of actual performance measures, but was not indicative of actual project performance.

Heat Exchanger Cause Summary

The TapRoot® standard terms are presented in the outline below. To be consistent with the TapRoot process, the team is using these standard terms, though in the discussion following the outline we have used the TapRoot standard terms in context of Fermilab processes

3) Equipment Difficulty
    a. Design
        i. Design Specifications
            1. Problem Not Anticipated
                a. Equipment Environment Not Considered
        ii. Design Review
            1. Independent Review Less Than Adequate
    b. Equipment / Parts Defective
        i. Quality Control

Heat Exchanger Cause Summary Discussion

Direct Cause

3 a.i.1.a - Equipment Environment Not Considered

The LHC Interaction Region heat exchangers were not designed to handle the 20 bar pressure to which they are subjected to during cool-downs and cryogenic system operational conditions.

The prototype design for this heat exchanger was a variant of a heat exchanger design used at CERN, which consisted of corrugated copper tubing brazed to a stainless steel end flange. A prototype, consisting of a short section of this tubing and mating flange, was pressure tested at FNAL to determine if the material was adequate for this design. During pressure testing of this short section, the tubing started to fail near the braze. The brazing annealed the first few convolutions of tube softening the material near the ends. In response to this observed failure, the design was modified by adding a tube to reinforce the ends. This revised design resulted in a successful pressure test.

Between the time when heat exchanger testing ended and the components were fabricated another engineer was assigned. He was given the responsibility to complete the design and procure the Heat Exchanger components. The revised dimension of the stainless steel sleeve was not noted in the Engineering Note and Drawings. Procurement and fabrication drawings did not indicate revised dimension of the sleeve support for the annealed section of copper. With design development and reviews not following a formal process, this change went unnoticed.

There was no pressure test of the fabricated, assembled heat exchanger unit prior to delivery to CERN and the error wasn't discovered until CERN had installed the Fermilab components into the LHC. During a pressure test, the units started to fail. Fermilab did pressure test the pressure vessel, which contains the heat exchanger, but the heat exchanger was open resulting in the same pressure being applied on both the inside and outside. As explained by interviewees, the test did not involve a differential pressure between the inside and outside of the heat exchanger as the heat exchanger itself was not considered a pressure vessel.

Contributing Causes

3)a.ii.1. Independent Review Less Than Adequate

The intended modification was not carried through to the final design. The original design was used as the specification to the vendor, rather than the modified design that resulted from the pressure test failures. In addition, the engineer did not specify a means of controlling the distance or the amount of the annealing during the fabrication.

The result is that the copper tubing was annealed beyond where the two inch stainless end flange supported it. During a pressure test at CERN, the heat exchangers started to fail, and upon inspection of the untested heat exchangers, several showed signs of damage. The damage to these units is believed to have happened during the cryogenic testing of the magnets at Fermilab.

Upon review of the final design drawings, it was determined that the heat exchanger components were designed and reviewed by the same engineer. There was no independent design review of the heat exchanger mechanical design and therefore no opportunity for another person familiar with the behavior of materials in a cryogenic, pressure-filled atmosphere to check the work done and highlight issues.

3)b.i. Quality Control

The first article testing of the heat exchangers produced in industry did not include vendor or in-house pressure testing requirements nor was there technical representation from Fermilab at the vendor site during the heat exchangers production runs. Testing should have discovered the design error and technical representation may have discovered the annealing or support issue, if it was present during fabrication.

Additionally, the prototype heat exchangers were tested to 7 bar at Fermilab, not the 20 bar operational pressure found at CERN. The tests at Fermilab were focused on several aspects other than pressure in operational conditions at CERN. Fermilab should have required testing of the production run and been at the manufacturer during fabrication; however, it was assumed that the fabrication would be adequately handled by the vendor.

The issue was further compounded because CERN's tests of the heat exchangers were focused on their ability to handle the thermal loads and also failed to perform pressure testing prior to installation in the LHC.

Common Cause Summary Discussion

Contributing Causes

2)e.i.1 - Standards, Policies, or Administrative Controls Incomplete

Fermilab does not provide formal training in project management nor provide a project controls manager or operations manager to assist lab personnel assigned as Project Managers. Absent this background and support, Fermilab project managers are left to fashion their own individual approach to project management processes, organizational structure and operational procedures (design, fabrication and assembly, testing and QA); this contributed to the failures within the devices. Typically, as a research lab, Fermilab draws upon its physicists to staff key roles in project management. This is not an issue in and of itself; however, as their expertise and primary focus is on scientific technical matters. Project management procedures and systems are not embraced and employed effectively in the project execution. This is evidenced by the following:

- Project management not fully understood or supported
    - The review of the project documentation revealed a full set of documents such as the Project Execution Plan, Quality Assurance Plan, Budget, Schedule, etc. All of the correct terms were used in the development of these items; however, with the exception of the budget and schedule, the project documents were "put on the shelf" and not used as a guideline. The Project Execution Plan had the appearance of project management plan which contained appropriate guidelines, was compliant with DOE requirements, and was not applied once complete.
    - Standard tools that one would expect to be used as part of a Project Execution Plan, such as risk management, were absent. Personnel interviewed were questioned about how risk was identified and abated. They stated that there was no risk analysis. This is especially poignant during the time when it was determined there would be no string test due to budget and schedule constraints. Additionally, a string test was never specified as a part of the US Project. CERN had planned from the beginning that the first complete assembly test would be when the magnet system was put in place in the LHC.

The decision not to perform the string test may have been a good one as tests and processes are considered and abandoned as part of any project. The issue from the project management process and system perspective is the failure to actually determine the cost and schedule impact and, if it was determined that the constraint is true, to perform a risk analysis of that decision. The project should systematically consider the elements of risk and how to mitigate them, or make a conscious decision to accept the risk.

Regarding the string test; items that should have been considered include understanding what information was going to be gleaned from the test if it was run, deciding whether there were any compensatory measures that could have been substituted for the test in a cost effective manner to give the project the same result, and the potential outcomes of not doing those things. Potential outcomes associated with failure could include safety and operational problems and denigration of Fermilab's technical prominence; leading to costly re-design, repair or replacement of components.

In the case of the string test there were other things that could have been done in lieu of a physical test such as commissioning an integrated model that ties the quadrupoles and DFBXs into triplet assemblies. The act of building the model would have driven questions such as where the 20 bar pressure comes from and how it is applied – which may have led to the discovery that the dynamic load had not been considered.

No such systematic review took place and it became widely accepted that the test could not be done due to budget and schedule constraints.

- The project lacked integration from the onset. Key items were not considered and acted upon:
    - Confusion about CERN versus Fermilab roles and responsibilities led to blurred lines when it came time to baseline the project. Responsibilities were not fully defined (e.g. determining who was responsible for design of CERN tunnel support systems for the IRs).
    - Agreements did not include Fermilab review of test plans for the equipment once it was installed at CERN. Fermilab's responsibility ended when the equipment was received and inspected by CERN. By not reviewing the test plans, or being part of the commissioning and startup of the accelerator, Fermilab lost the opportunity to understand how their equipment was to be used and the commensurate operational parameters it would encounter. If Fermilab had reviewed the test plans it may have keyed them to consider the dynamic pressure loading.
    - The organizational chart showed a systems integration manager that was initially filled, but was later vacated to assist LBNL in recovery of the DFBX project. The decision not backfill the position was made in response to budget constraints. In addition, there were mixed responses to describing the role of the integration manager which varied from a part-time position to integrate components between the LBNL, BNL, and Fermilab to a full-time position involved with integrating the work within the fence at Fermilab.

The result is that no one in the project was questioning how these components would fit together or whether the integrated components, as a system, would meet performance specifications/operational requirements at CERN.

Traditional projects of comparable size combine the integration and risk management roles so that there is an individual whose sole purpose is to be concerned with the integration of system components and assessing risk to the project.

- The project did not execute a lessons learned program. Many of the participants were involved with Tevatron, upgrades and new construction at Fermilab, and the SSC yet there was no group discussion at the beginning of the project to develop a list of lessons learned from those projects for application to the LHC.
- The project did not avail itself with expertise outside of Technical Division. There were experts in cryogenics in the Accelerator Division as well as modeling expertise in PPD. These assets could have been used for reviews or to augment Technical Division staff during times of heavy workload. As a result, there was no truly independent second checking of the work within the Fermilab fence.

Distraction

- Cost and schedule control
  - The cost elements of the schedule were developed with varying levels of basis; the fabrication portion was fairly well known as it was based on experience from the RHIC magnets at BNL while the R&D component was less developed.
  - Fermilab, BNL, and LBNL were allocated 40/40/20% of the project budget respectively. The team could find no evidence that the project coupled the capability to perform the scope to the funding levels awarded the sites. In addition, in 1996 it was decided to de-scope the project to meet budget restrictions resulting in realignment of scope between the laboratories. At that time, the responsibility for the DFBX was shifted to LBNL who, in retrospect, was not qualified to design and build the component.
  - It was approximately three and one-half years into the project before problems with the DFBX were acted upon. Project personnel had reported that the design was complete and ready to build, but was not. A key Fermilab employee was re-assigned to work extensively with LBNL, as well as the assignment of a new chief engineer at LBNL, to recover the project.
- Management systems
  - It was apparent that Fermilab senior lab management was not actively engaged in the project execution. Once the project was funded the PM was essentially on his own. He reported to the Fermilab Director who looks at projects from a Level 0 budget and schedule perspective, as is appropriate, and guidance from the head of the Technical Division focused more on staff resources. Without guidance or limitations, the only oversight fell to project

reviews which, by their nature, are not detailed enough to discover the issues that caused the events. An experienced senior manager may have discovered that the design reviews were not adequate and directed the PM to commission a review to confirm design basis calculations and drawings. This did happen when the current Fermilab Director commissioned an in-depth design review of the suggested repairs of the Fermilab LHC components following the failure in the LHC. The project had again performed a summary review (PowerPoint®) when the Director stepped in and made the in-depth review a requirement. Participants in the review provided positive feedback that this type of review added value to the design process and that it should be used more regularly in future design efforts.

- There was no recognition of when the project transitioned from the R&D phase to the design-build phase. Because it was not recognized, R&D continued to occur well into the design-build phase causing changes to occur while the Technical Division was attempting to put systems together. A point in the project could have been picked where no more R&D inputs would be accepted to allow focus on production. At the same time, R&D efforts could have been directed to the LARP for future consideration and upgrade of LHC, once operational.
- Collaboration versus vendor relationships can have a negative affect if not managed properly. On the positive side, collaboration can result in the supplied components being closer to what is required by the customer. On the negative side, collaboration can lead to a less formal relationship where scope, schedule, and funding limitations can be ignored in favor of providing a better product. This project was more collaborative, and both of the above happened to some extent, neither of which presented a major problem for Fermilab or CERN.

  It is mentioned in this report because it was brought up by almost every person interviewed when discussing key milestones and deliverables. The point of those interviewed was that a project can have a collaborative or vendor relationship, but not both. The team disagrees.

  A project can be collaborative with certain key milestones agreed to by both parties. This is particularly valuable when the project is setting a date when all parties will understand performance specifications. This will have a positive impact because all parties will be able to plan resources to make that happen, which they can then work collaboratively to define. Without that occurring, the project can get to a point where one party is ready to fabricate their components and another is still in design, which ultimately impacts the project's ability to deliver a final, integrated product on time.

Root Cause Discussion

2)e.i.1 - Standards, Policies, or Administrative Controls Incomplete

Root Cause Statement

Fermilab engineering management controls do not include codified, standard design process requirements that include a systems integrated design, design review, and documentation recording and archival process. Instead, Fermilab relies upon individual contributors to obtain review of design basis calculations and recognition of interface and integration requirements. In both instances, the lack of documentation and in-depth review resulted in critical design errors being missed until the components were tested *in situ* at CERN.

Root Cause Discussion

If the controls had been in place to check and review design and view the devices as an integrated system, the direct cause of an error in design would more likely have been caught and would probably have not made it through the process to fabrication and delivery. Put another way, controls, also referred to as barriers, should be in place to catch and correct issues such as the ones that happened during this project.

Similar Issues

Senior management interviewed at Fermilab and DOE drew the Team's attention to similar experiences regarding the design and fabrication of components and systems, one of which is presented in a summary format, below. This, and other similar issues, leads the Team to conclude that the issues encountered in the LHC project are not limited to this project.

- Main Injector Project
    - The installed system piping wasn't what was specified (i.e. did not have full penetration welds)
    - The vendor did not perform required QC checks (i.e. weld-joints weren't X-Rayed to verify a full penetration weld)
    - Fermilab did not have quality assurance inspectors to verify welds at the point of fabrication/manufacture and did not demand to see the X-Ray films to verify the welds
    - Fermilab performed hydrostatic test improperly
        - Used tap water in a stainless steel system
        - Left system in wet-layup with tap water
    - Welds were attacked and leaked while in layup
    - All welds had to be re-worked at an expense of over $1.5M

Root Cause Conclusion

The current competitive environment presents new challenges in the way that projects are funded and executed.

- Funding sources are limited and grants are more restrictive in terms of expectations and oversight requirements.
- High-Energy Physics projects are large and costly resulting in an increased use of collaborative ventures between laboratories, academic institutions and international research organizations.
- Government funding sources require increased scrutiny of the project execution to ensure each participating member of the collaborative venture meet its obligations:
    - Performance criteria must be identified and met in accordance with project scope
    - Systems and components must work in the intended operating environment
    - Interface requirements must be included in design
    - Risk must be understood and mitigated
    - Projects should be managed within budget and schedule constraints.

Meeting the challenges of the current competitive environment, coupled with the desire to host the ILC at Fermilab, warrants modification to the way that projects are managed.

Recommendations

The following recommendations were derived from the cause sections, above. They directly answer the issues discussed, and for the most part, can be implemented in lieu of current requirements. The team has made every effort to minimize administrative burdens.

In addition to the recommended actions, the Team strongly urges Fermilab to commission a Process Improvement Team to develop guidelines for Fermilab on how to improve its approach to executing both inter-laboratory and international collaborative projects. It is the Team's opinion that this type of relationship will be more prevalent in the future and needs to be addressed to make Fermilab a success and a serious contender for future international projects, such as the International Linear Collider.

Finally, the Team wishes to put the recommendations into context. The team was asked to perform a critical look at issues at Fermilab regarding their performance. The issues discussed are comprehensive and valid; however, there is a scalability issue to be recognized regarding adopting the recommendations. It is based entirely upon the assumed future of Fermilab. When deciding which of the recommendations to follow, and to what level, the Fermilab strategic plan should be addressed and a few pointed questions should be asked:

1. Is the laboratory safe without adding this requirement? For the most part, yes although one could make the argument that an undiscovered design flaw could easily lead to adverse impact on personnel safety.

2. Can Fermilab continue the way it has for the past 40 years? Yes, the process has worked so far and will probably work in the future although changing a few of the processes will result in reduced issues and rework and; therefore, more money available for science versus re-work.
3. Can Fermilab count on the ILC or other large project coming here? No. The Fermilab processes will not endear the laboratory to international site selection committees if it continues to have the types and frequencies of project issues it has experienced.

   While a decision to retain its current practices will not result in Fermilab's immediate demise, it may result in the site being passed over in favor of others when it is time to decide where to host the next large accelerator project.

The following are specific recommendations the Team believes will have a positive impact on the laboratory, both now and in future endeavors in the international HEP community.

- Project Planning
  - Projects should include a standard kickoff process during the formation of the project which covers major elements, how they are going to be controlled and by whom, project issues and risks, and performance expectations. At a minimum, the meeting should be held over a period of days, but may expand to one or two weeks depending upon project size and complexity, as required to cover the following:
    - Brainstorming the approach
    - Identifying lessons learned from previous projects of a similar nature. A small investment in time up front will pay large dividends in avoided rework later.
      - This should be an ongoing effort that continues to capture lessons learned for the current and future projects. The lessons learned should be archived and be available to other project personnel.
      - To be effective, incidents and/or events during design, procurement, fabrication and testing should be accurately and thoroughly documented to capture the facts of the issue, what was done to immediately correct the issue, and what was changed to prevent recurrence.
    - Discussing how risk is going to be identified, calculated, managed, and mitigated.
      - Known issues, risks, and associated mitigating actions should be identified and tracked from the beginning of the project
      - Identification of potential issues that can't initially be qualified or quantified should be noted for monitoring during the project execution.
    - Identifying project constraints on the project in terms of budget, schedule, manpower, and known operational issues.

- Identifying, discussing, and assigning key project members roles and responsibilities:
    - Project Manager and Deputy
    - Finance
    - Procurement
    - Integration and Risk Management Manager
    - Project Technical Lead
    - QA
    - Project Controls
- Discussing what inter-divisional participation will be sought to augment the project and how it will be managed.
- Developing test plans and identifying testing environments
- Documenting the known operational environment. This will lead to the identification of knowledge gaps or areas that will require additional work to develop, and should involve a considerable effort.
    - This exercise should develop a list of performance and operational specifications with associated actions to fill the gaps.

Project Controls - Project controls should be codified to describe how projects will be managed at Fermilab:

- Budget and cost management should use a qualified Earned Value Management System to track and control costs.
- The project should generate and archive the Basis Of Estimate (BOE) for all major project elements.
    - Develop and maintain a resource-loaded baseline schedule
- A risk-based change management process should be established that identifies variance threshold reporting and action requirements.
- Contingency versus management reserve should be identified. Traditionally, management reserve is the portion of the project funding withheld from the project participants by the Project Manager that can be released for overruns and changes to estimated project elements. This should be separate from contingency funds which are typically assigned for changes in scope or timing of deliverables brought on by changes in schedule outside the PM's position.
- Schedule management
    - The schedule should contain hard schedule requirements (3-5% of project cost) that are inviolate. This will ensure that certain key elements are not deleted to improve the financial condition of the project.
        - As a standard practice all project baseline budgets and schedules should include specific activities and resources for engineering review, testing and other QA activities. These activities and budget items should be independent of the project contingency. Recommend at least 3-5% of the project budget be typically allocated to these sets of activities.

        - The schedule should also contain a formal break point milestone transitioning from R&D to production negotiated between the supplier or owner of the ultimate product and the vendor/collaborator
    - Project documentation
        - Risk analysis: a formal risk analysis should be conducted and documented at the conclusion of conceptual design and the mitigation strategies incorporated in the project baseline budget and schedule (in accordance with DOE O 414.1C). The risk analysis should be updated and reviewed at each subsequent design review milestone and at least quarterly during the fabrication, installation and commissioning phase.
    - Systems Integration Role: For any complex or collaborative project the engineering/PM organization should budget and staff a specific role for ongoing systems integration. This role should continually oversee how the technical managers are addressing integration issues, conduct regular systems reviews, highlight configuration or requirements changes that each technical designer needs to keep current, and coordinate sharing of integration issues and solutions among all team members. This person may also serve as the risk manager on smaller projects.
        - There needs to be a continual updating and communication to all team members of changes to the functional requirements as designs progress or project conditions change.
        - Parallel to the systems role, on international projects, there should be a code conformity document to guide the development so that the devices function as anticipated in under the standards and performance codes of the operational environment
- Design and Engineering Process

  The design and engineering process at Fermilab currently follows a distributed model where engineers and scientific personnel fulfilling engineering roles are assigned to separate divisions based upon need. This is in contrast to some laboratories where the engineering function is centrally controlled and engineering support is matrixed to other organizations as needed to support their projects.

  Both approaches have their individual merit; the two primary themes identified are the lack of control and integration with the distributed model and the lack of attention for smaller, shorter-term projects under the centralized model. The Team did not evaluate which would work better at Fermilab; however, it does recommend that a Fermilab Chief Engineer position be created. The Chief Engineer should be the engineering process owner and publish a centrally-controlled design/engineering manual and implementing procedures that govern how that function is controlled at Fermilab, which would be mandatory for all engineering processes at Fermilab. The Chief Engineer could also be called upon by the OPMO and Project Management to select qualified individuals and lead design/engineering reviews.

The Design/Engineering Manual should contain elements that govern reviews, data archive, process, etc.:

Design Reviews:

- Templates and checklists for what materials must be produced by design teams in advance of each review, to include calculations, design bases etc. These will provide an internal QA tool for the engineering team and provide the required materials to allow comprehensive independent technical reviews. These templates should be incorporated in a design review procedure. The checklists will help ensure that all elements of the design are reviewed including inter-disciplinary checks and all specifications, boundary conditions, testing requirements, and operational environments have been considered and appropriately applied.
- Design reviews should include technical experts from outside the team and in certain cases outside of the lab. This will assist in providing fresh independent assessments of completeness. A budget to pay for this reviewer's time from outside the team or from outside experts should be established so cost is not a constraint. A team of on-call resources to assist in these reviews should be assembled through contract resources ahead of time so they can be engaged quickly as required.
- Review Formats: The design reviews should include sufficient time for on-board review of specification/drawings assumptions etc. The review team should have time to review these materials in an independent manner. The review team should prepare its own set of written comments and suggestions and then be engaged subsequently to review how the design team addressed or incorporated the comments. The "presentation" or PowerPoint® review portion should be limited so as not to conflict with the time required to perform technical reviews (or alternatively advance material such as in a PP format could be emailed to the review team in advance of the review meeting to facilitate their being aware of progress since the last meeting in advance of the current meeting).
- The current changes to the functional requirements and specifications should also be a component for each technical design review to verify that the current design is consistent with the current requirements.

Design Process Management

- Establish a configuration control system for design efforts
- Define design basis archive requirements and establish a central library where such information is stored and available for future use
- Define the requirement for design basis cross-checks. This includes calculations, drawing generation, and interface requirements reviewed both internally and between sub-element projects designing specific, but separate, components.

  - Archive R&D design specification development and control. Include items such as ideas tried and abandoned, and why; shop floor changes, reason, and impact; and results of tests against a prescribed (assumed) specifications.
  - Define the change management process using a risk-based graded approach that defines who can authorize changes and under what circumstances.
  - Develop a process that identifies critical designs and the extra requirements to control them
- Training
  - The Team recommends that formal training for Project Managers be developed or procured. This training will be helpful to those managing projects at Fermilab so they can learn to manage the projects versus being led by them.
  - Develop orientation for engineers or employees performing the engineering process so they understand the processes employed at Fermilab
- QA Program
  - The lab/engineering organization should prepare and compile an ongoing electronic database of "lessons learned" from engineering reviews, testing results and other failure lessons that are available to all personnel across all disciplines. (Analogous to safety incident reports/near miss reports etc.) This will improve the sharing of information across divisions, labs and project teams and provide a useful tool for training of engineers and PM teams. This is increasingly important as more and more projects will be collaborations among divisions, laboratories and universities.
  - All project budgets and schedules should include specific activities for quality assurance such as design reviews, factory inspection, system testing etc. and these budgets and schedules should be distinct from "contingency" activities. This will elevate these activities in importance and require any deviation from them for budget and schedule considerations to be more formally considered. (see budget and schedule).
  - Fermilab is currently developing a Quality Assurance Plan and implementing documentation. This should include elements that direct quality implementation using a risk-based graded approach. It should also include the adoption of a Quality Assurance Inspection program that defines how inspections will be conducted and a qualification program to standardize how these inspections are performed. The qualification program should be performance based that includes a combination of classroom and on-the-job training against a qualification standard managed by the senior (QAI Level III) qualified Quality Assurance Inspector.
  - The fabrication process traveler should include a review by the resident QAI – III to concur with QA stop and hold points.

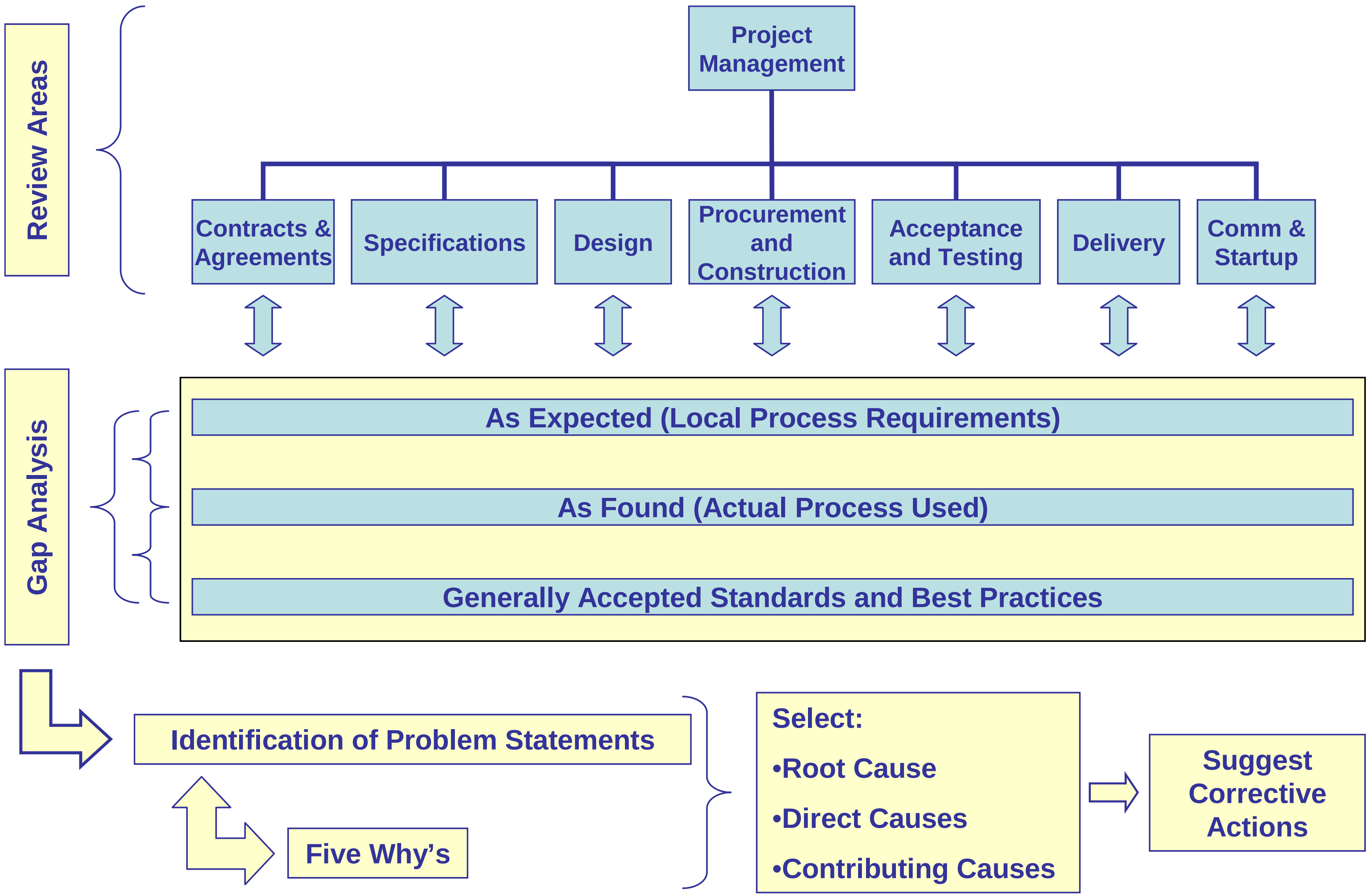
Supporting Documentation

The Team used a combination of document reviews, collection of statements, and interviews in the conduct of the root cause analysis. Documents containing the results of the process review are provided as supporting documentation to Fermilab at the conclusion of the review and include:

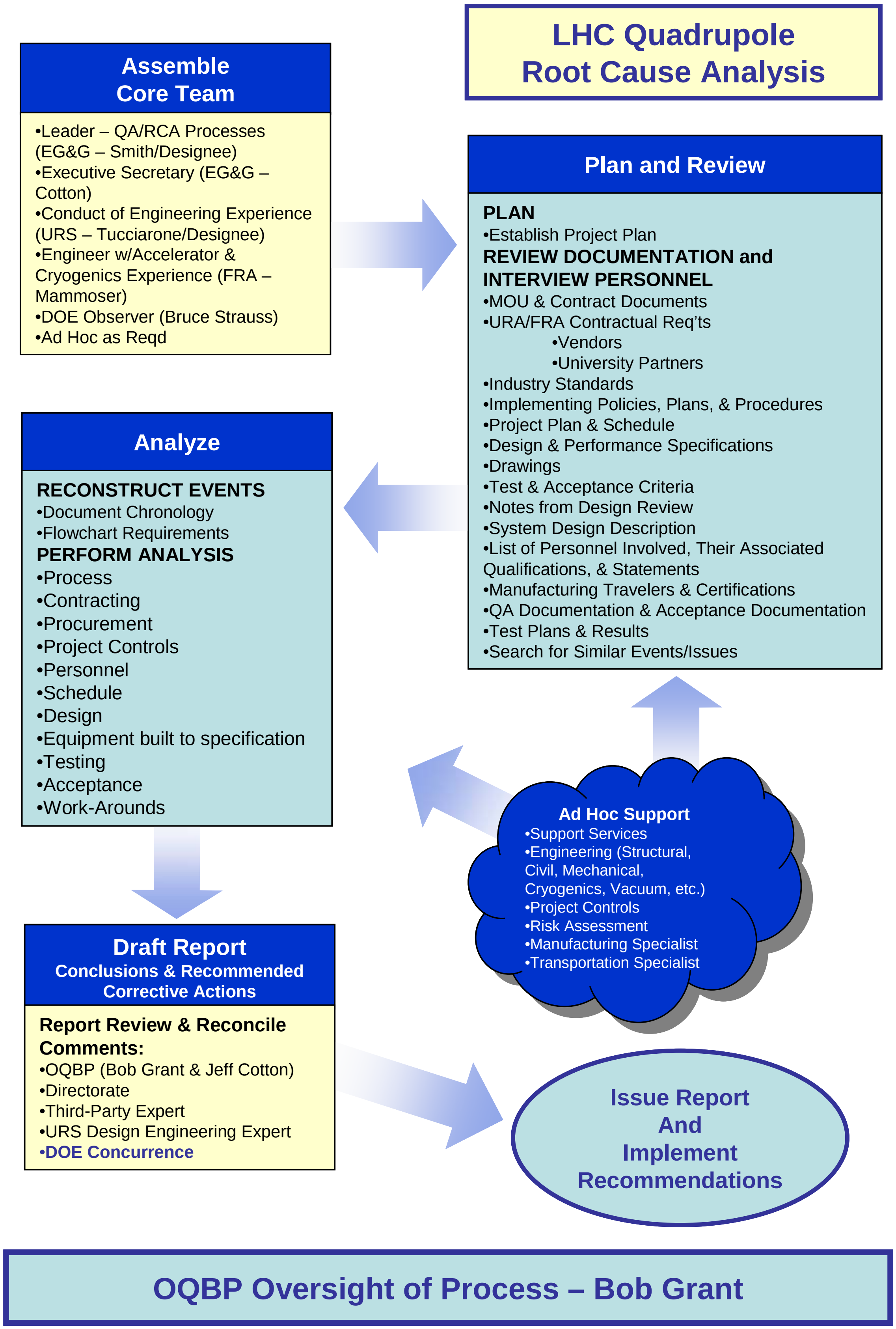
- Statements by project personnel
- Interview notes
- Functional area review discussion
- Question matrix
- Ishikawa diagram
- Event and Causal Factor Charts
- Timeline

Attachments

Attachment 1, Page 1 – Root Cause Analysis Flowchart



Attachment 1, Page 2 – Root Cause Analysis Flowchart



Attachment 2 – Personnel Interview List

BNL

Mike Anerella, Chief Engineer

CERN

Ranko Ostojic, Specialty Magnet Manager (current)
Tom Taylor, Specialty Magnet Manager (former)

DOE

Bruce Strauss, Program Manager
Jim Yeck, Project Manager
Pepin Carolan, Project Manager

Fermilab

Barbara Brooks, Workforce Development & Resources Section Deputy Dept. Head
Bob Kephart, Technical Division Head (2002-2005)
Cindy Conger, Chief Financial Officer
Connie Trimby, Laboratory Financial Planning Manager
Dean Hoffer, Office of Project Management Oversight
Ed Temple, Office of Project Management Oversight Head
Fred Nobrega, Quadrupole Cold Mass Project Engineer
Greg Kobliska, Technical Division Procurement Manager
Jamie Blowers, Technical Division QA
Jay Theilacker, Cryogenics Dept. Head, Accelerator Division
Jim Kerby, Fermilab LHC Accelerator Project Manager
Jim Strait, US LHC Accelerator Project Manager
John Peoples, Former Fermilab Director
John Zweibohmer, Technical Division Deputy Procurement Manager
Mike Lamm, Quadrupole Integration and Testing Scientist
Paul Czarapata, Accelerator Division Deputy Head
Peter Limon, Former Technical Division Head
Phil Pfund, US LHC Accelerator Engineering Manager
Roger Bossert, Quadrupole Magnet Cold Mass Engineer
Steve Holmes, Associate Director for Accelerators
Tom Nicol, Quadrupole Cryostat Project Engineer
Tom Page, Quadrupole Cryostat and Interconnect Engineer
Tom Peterson, Quadrupole Cryogenics Engineer

LBNL

Joseph Rasson, DFBX Project Engineer